DOE/ID/01719--4
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REPORT ~~GU/ID 1719-4~~

DOE/ID/01719--4

**GEOHERMAL BINARY-CYCLE WORKING-
FLUID PROPERTIES INFORMATION**

MASTER

Annual Report

DOE/ID/01719--4

DE82 019330

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Work Performed Prior to December 31, 1979 (Except for Diagrams)
Report Released September 30, 1981

Prepared For
The Department of Energy

Under Contract

No. EW-78-S-07-1719

ASO 7-78 ID 01719

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ABSTRACT

The research discussed in this report was performed at the University of Oklahoma prior to December 31, 1979. The report was not released until September 30, 1981, so that pressure-enthalpy diagrams for a number of potential geothermal binary cycle working fluids could be prepared in SI units. Efforts were directed principally to working fluid thermophysical property correlation and presentation of properties information. Pressure-enthalpy diagrams are presented for propane, normal butane, isobutane, normal pentane, isopentane and propylene. Generalized correlations are presented for the thermodynamic and transport properties of hydrocarbon pure and mixture working fluids. Specific correlations are presented for the thermodynamic properties of 27 fluids and for the viscosity and thermal conductivity of hydrocarbons including isobutane and isopentane.

1. INTRODUCTION AND OVERALL SUMMARY

The material presented herein has been brought together in an attempt to provide, in a single document, a major portion of the information needed for the calculation of geothermal binary cycle working fluid properties. The working fluids considered include hydrocarbons and halocarbons. The accuracy levels of the correlations presented are generally sufficient for conceptual design studies. For isobutane, correlations with accuracies approaching those required for detailed design are presented. Data needs for isobutane, isopentane and isobutane-isopentane mixtures also are discussed.

Section 2 presents a brief discussion of thermophysical property data and correlation accuracy requirements for geothermal binary cycle working fluids. It is pointed out that property accuracy requirements are higher for detailed design than conceptual design. Section 3 provides a brief summary of the status of application of the MBWR (Modified Benedict-Webb-Rubin) equation of state to twenty-seven pure fluids, including a number of geothermal working fluids. The MBWR equation coefficients and other pertinent information are presented in Appendix 1 and pressure-enthalpy properties diagrams for propylene, propane, isobutane, normal butane, isopentane and normal pentane are presented in Appendix 2. Section 4 presents a discussion of generalized correlations which can be used for working fluid thermophysical properties calculations in conceptual design

studies. Although these correlations were developed in earlier research, the correlations which have not been published in the open literature are given in Appendix 3 for completeness, so that the present report will provide unpublished information necessary for the calculation of working fluid thermophysical properties in conceptual design studies. Section 5 presents a discussion of experimental thermophysical data needs for isobutane, isopentane and isobutane-isopentane mixtures. Appendices 4-8 provide the details of data needs studies for isobutane, isopentane and an 80 mole percent isobutane-20 mole percent isopentane mixture, along with correlations for isobutane and isopentane pure fluid thermophysical properties.

2. THERMOPHYSICAL PROPERTY DATA AND CORRELATION ACCURACY REQUIREMENTS

There are two major design situations in which geothermal binary cycle working fluid thermophysical property information has been needed by the geothermal industry. One situation is for initial conceptual design studies; the second is for detailed design of plants which will actually be constructed or which are under serious consideration for actual construction. The required accuracy levels of thermophysical properties used in these two design situations differ considerably. For conceptual design studies, it is usually important to compare the use of different working fluids, different operating conditions and different cycle configurations. For these purposes, it is important that (1) the essential features of fluid behavior for individual fluids be accurate and (2) the relative differences in behavior from fluid to fluid be accurate. Thus, although absolute accuracy would be desirable, accurate representation of relative behavior, from state condition to state condition and from fluid to fluid, is important for conceptual design studies. On the other hand, for detailed design, high accuracy for the specific working fluid is mandatory.

Because it is the usual practice in modern day design to use properties correlations, the accuracy requirements for experimental data are dictated by the accuracy requirements for correlation purposes, in order to achieve the needed accuracy in

design calculations. For pure-fluid thermodynamic properties, in order to achieve design calculation uncertainties of less than 1% for density, 1% for vapor pressure and 2 Btu/lb for enthalpy, the experimental data used to develop the correlation should have uncertainties of approximately 0.1% for density, 0.5% for vapor pressure and 1 Btu/lb for enthalpy. For mixtures the situation is similar, with vapor-liquid equilibrium and if possible, dew point, bubble point, and excess property data used in place of vapor pressure data. Measured mixture mole fractions should have uncertainties of less than 1% or 0.005, whichever is larger, in order to adequately correlate mixture properties for design purposes. For the correlation of viscosity and thermal conductivity, the experimental data should have uncertainties of less than 1% for correlation within 2%. It should be noted that if possible, correlations should not be used outside the range of the data used in developing the correlation. Therefore data procured for correlation development purposes should extend beyond the range of the region in which the correlation will be utilized.

Keeping the above factors in mind, we present herein generalized correlations which can be used for conceptual design studies and evaluations and specific correlations of isobutane and isopentane data pertinent to considerations of detailed design needs.

3. AVAILABLE PURE WORKING FLUID THERMODYNAMIC PROPERTIES CORRELATIONS AND PROPERTIES DIAGRAMS

The thermodynamic properties of a number of pure fluids, including certain geothermal binary cycle working fluids, have been correlated using the MBWR (Modified Benedict-Webb-Rubin) equation of state. MBWR parameters for fifteen pure compounds were presented in 1973 (1), along with properties tabulations and pressure-enthalpy properties diagrams in engineering units. The fifteen fluids considered were the normal paraffin hydrocarbons methane through normal octane, isobutane, isopentane, ethylene, propylene, nitrogen, carbon dioxide and hydrogen sulfide. A number of these fluids are potential geothermal binary cycle working fluids. Because certain halocarbons also are potential working fluids, a study was performed to determine the capability of the MBWR equation to describe halocarbon thermodynamic behavior. The results were satisfactory and MBWR parameters for eight halocarbons were determined (2). MBWR parameters for water and ammonia were determined in other studies and the MBWR parameters for 27 pure fluids were presented in a summary manuscript (2), which has been updated and is presented herein in Appendix 1. Pressure-enthalpy thermodynamic properties diagrams in SI units have been prepared for several fluids using the MBWR equation with the parameters in Appendix 1; the diagrams for six potential working fluids are presented in Appendix 2. These fluids are propylene, propane, isobutane, normal butane, isopentane and normal pentane. It is believed that the use of the MBWR equation of state with the parameters

given in Appendix 1 is adequate for conceptual design studies for individual pure working fluid binary cycles. In most cases, the accuracy is sufficient for detailed design, so long as operating conditions are not in the near critical region. Certainly, equation parameters for the MBWR equation have been determined for more potential working fluids than any other equation of state.

4. GENERALIZED THERMOPHYSICAL PROPERTIES CORRELATIONS WHICH CAN BE USED FOR CONCEPTUAL DESIGN STUDIES

In the performance of conceptual design studies, it is not always possible to have thermophysical properties information available for the working fluid of interest. This situation is especially true when mixtures are considered as working fluids. In these cases generalized correlations generally must be used. Recent experience has demonstrated that the most accurate available generalized correlations of fluid thermophysical properties have been based on the principle of corresponding states. For hydrocarbon mixture thermodynamic properties the MBWR equation of state has been cast in the form of a three parameter corresponding states correlation with reasonable results (1,3). For hydrocarbon viscosity and thermal conductivity, three parameter corresponding states correlations have been developed which can be used for both pure fluids and mixtures. The development of these correlations was sponsored by the Gas Research Institute and American Gas Association (4).. Because these viscosity and thermal conductivity correlations have not appeared in the open literature, the correlation details are given in Appendix 3. Predicted viscosity and thermal conductivity values for pure hydrocarbons should be adequate in most cases for detailed design, while mixture viscosity and thermal conductivity values should be adequate for conceptual design studies.

5. THERMODYNAMIC AND TRANSPORT PROPERTY DATA EVALUATION AND CORRELATION FOR ISOBUTANE, ISOPENTANE AND ISOBUTANE-ISOPENTANE MIXTURES

This task has involved searching the literature for data, evaluation of the available data and recommendation of the data procurement and correlation efforts needed to meet geothermal industry needs for isobutane, isopentane and isobutane-isopentane mixtures. This work has been carried out as a cooperative effort with other centers for geothermal research, principally Brown University, the Idaho National Engineering Laboratory and other Department of Energy offices and laboratories, the National Bureau of Standards and the Electric Power Research Institute. The working fluids considered to be prime candidates for geothermal binary cycles in 1978 were emphasized in this effort. The data considered were thermodynamic property data, viscosity data and thermal conductivity data. Two fluids were considered in some detail, isobutane and isopentane. Isobutane is the working fluid for the first 5MW Raft River power plant, while isopentane is a prime candidate working fluid for the second Raft River 5MW power plant, which will use direct contact heat exchange. Some work also was done to evaluate thermodynamic property data needs for an isobutane-isopentane mixture (80 mole percent isobutane) considered as the working fluid in design studies for the 50MW Heber power plant. However, the effort for this mixture was curtailed when plans for the Heber plant became uncertain early in 1978. Summaries of the results of the effort to identify data needs for these fluids are discussed below. It should also be noted that Brown University has performed an evaluation of

isobutane data and correlations and has presented a compilation of isobutane thermodynamic and transport property data (5).

5.1 Isobutane Thermodynamic Properties

An evaluation of available thermodynamic property data for isobutane was carried out early in 1978. This evaluation led to recommendations for isobutane data procurement which were transmitted (on March 23, 1978) to Max Klein of NBS for consideration in planning the DOE sponsored isobutane data program at NBS (6). The experimental program at NBS has supplied a good portion of the recommended data (7). Pertinent correspondence (6,7) is given in Appendix 4.

The following points were emphasized in our recommendations in March, 1978. (1) Vapor phase density data in the turbine expansion region should be obtained and because the data of Sage and co-workers (8) and Beattie and co-workers (9) disagree, vapor phase density data in the region of overlap should be obtained (1). Vapor pressure data in the range of geothermal cycles should be obtained and because of data disagreements, the range of the data would be most valuable from 0 °F to the critical temperature (274 °F). It was noted that in the absence of accurate calorimetric data, the vapor pressure is extremely important since the enthalpy of vaporization must be defined through the vapor pressure using the Clapeyron equation. It was also noted that if the measured density data in the vapor phase disagree with the data of Sage and co-workers (8) then the available compressed liquid density data could become suspect, since the only data source in this region is the work of Sage and co-workers. A potential need for

calorimetric data also was pointed to in the event a self consistent set of density and vapor pressure data could not be defined.

The isobutane vapor pressure data (77 °F to 257 °F) pressure and density data (two isotherms at 170 °F and 250 °F) reported by NBS in 1978 have provided an important measure of reconciliation of the isobutane data questions. It probably is correct to say that there are indications that there was no prior source of isobutane vapor density or vapor pressure data which was highly accurate in the range of isobutane geothermal binary cycles. On the other hand, for cycle operating conditions avoiding the critical region, the use of several published correlations of isobutane thermodynamic behavior have been adequate for much of the engineering design work performed to date in the geothermal industry. Improved representation of isobutane thermodynamic behavior is needed, however, if isobutane is utilized extensively as the working fluid for geothermal power plants. The new data obtained by NBS offer the opportunity for improved correlation of isobutane thermodynamic behavior; one such correlation is presented in Appendix 5.

5.2. Isobutane Viscosity

The literature search and subsequent evaluation of available isobutane viscosity data has indicated that the available data are adequate for present geothermal industry needs. Data from two major sources, Agaev and Yusibova (10) and Gonzalez and Lee (11), which cover the entire range of geothermal cycle operating conditions, are in substantial agreement. The isobutane

viscosity data and a correlation of the data are discussed in greater detail in Appendix 6.

5.3. Isobutane Thermal Conductivity

The literature survey for isobutane thermal conductivity data disclosed only one data source which covers the entire range of geothermal cycle operating conditions, the data of Kazaryan and Ryabstev (12). These data appear to be self consistent but their accuracy is difficult to assess. A comparison with a recently developed generalized thermal conductivity correlation (4) yielded an average absolute deviation between the predicted and experimental values of four percent. For most engineering design problems in the geothermal industry, an uncertainty of four percent in the thermal conductivity probably can be tolerated. Therefore, assuming the available thermal conductivity data for isobutane have an average uncertainty no greater than four percent, there is little cause to initiate a major data procurement program. A small program to obtain check points over the range of geothermal cycle operating conditions is recommended. Recommended calculation methods for isobutane thermal conductivity are given in Appendix 6.

5.4. Isopentane Thermodynamic Properties

A literature survey and a subsequent analysis of the available thermodynamic data for isopentane disclosed a situation similar to that previously found for isobutane. There are large discrepancies between the data of different investigators, both for

density and vapor pressure. Further, there are virtually no calorimetric data for isopentane. Our recommendation for data procurement for isopentane thermodynamic properties therefore follows along the same lines as our earlier recommendations for isobutane. If isopentane is to be used as a geothermal cycle working fluid, sufficient vapor pressure and density data in the range of cycle operating conditions should be obtained to reconcile the discrepancies between existing data or establish an accurate new basis data set from which accurate correlations can be developed. A correlation of isopentane thermodynamic behavior using available data is presented in Appendix 7.

5.5. Isopentane Viscosity

Only one data source for isopentane viscosity data which covers the entire range of geothermal cycles was found in a survey of the literature, the data of Yusibova and Agaev (13). A recently developed generalized correlation for viscosity (13) was found to be capable of predicting the viscosity data of Yusibova and Agaev with an average absolute deviation of 4.77%. Thus, the average uncertainty in the data probably is no greater than five percent, which is adequate for most engineering design calculations for geothermal cycles. In addition, the isobutane viscosity data of these same investigators, Agaev and Yusibova (10), were in essential agreement with the isobutane viscosity data of Gonzalez and Lee (11), so it is reasonable to assume that the isopentane viscosity data of Yusibova and Agaev (13) are of similar accuracy. We estimate the probable absolute

average uncertainty of the isopentane viscosity data of Yusibova and Agaev to be no greater than 5% and perhaps below 2%. Therefore, unless isopentane receives extensive use as a geothermal working fluid a major data procurement program for isopentane viscosity data is not recommended. A small program to obtain check points over the range of geothermal cycle operating conditions is recommended if isopentane is used in major future geothermal cycle projects. A correlation for isopentane viscosity is presented in Appendix 6.

5.6. Isopentane Thermal Conductivity

A literature survey for isopentane thermal conductivity data failed to locate data covering the range of geothermal cycle operating conditions. The only isopentane thermal conductivity data located were at atmospheric pressure, from four different investigators. Thus, it is recommended that a complete program for isopentane thermal conductivity data measurement be implemented if the use of isopentane as a geothermal binary cycle working fluid is planned for a major project. Such a program would require accurate measurement of isopentane thermal conductivity over the complete range of geothermal cycle operating conditions for direct use of the data and over an expanded region beyond operating conditions for accurate correlation of the data in the operating range. Estimated thermal conductivity values for isopentane from a generalized thermal conductivity correlation presented in Appendix 6 can be used for conceptual design studies until experimental data become available.

5.7. Isobutane-Isopentane Mixture Thermodynamic Properties

A preliminary evaluation of data needs for a mixture of isobutane and isopentane containing 80 mole percent isobutane was performed. The only mixture thermodynamic data available were the enthalpy difference data obtained by the C. F. Braun Company under the sponsorship of the Electric Power Research Institute. These data, which were subsequently published (14), were provided to the present project prior to publication by Gary Underhill of the Electric Power Research Institute (15). A preliminary evaluation of data needs was then provided to EPRI (16). The pertinent correspondence (15, 16) is given in Appendix 8. The correlation in reference 1 yielded predicted enthalpies with an average absolute deviation of 5 Btu/lb from experimental values.

The major conclusions from this preliminary study were (1) the calorimetric data for the 80 mole percent isobutane - 20 mole percent isopentane mixture probably were adequate for use in design, (2) phase equilibrium data were needed to define dew and bubble point loci more accurately than was possible from the calorimetric data and (3) accurate vapor and liquid density data and vapor-liquid equilibrium data were needed to adequately correlate the thermodynamic behavior of the mixture.

Subsequently, efforts were made to estimate the accuracy of the generalized corresponding states correlation in references 1 and 2 for prediction of the thermodynamic properties and vapor-liquid equilibrium behavior of isobutane-isopentane mixtures.

Data were lacking for isobutane-isopentane mixtures but were available for the corresponding normal paraffin isomer system, normal butane - normal pentane. Therefore, estimates of calculated isobutane-isopentane system densities, dew and bubble points and K-values were obtained by study of the normal butane - normal pentane system, using the data of Kay and coworkers (17). The experimental mixture composition closest to the geothermal working fluid composition of 80 mole percent isobutane - 20 mole percent isopentane is the composition 75.18 mole percent normal butane - 24.82 mole percent normal pentane mixture. Table 1 presents a comparison of calculated and experimental dew point and bubble point temperatures for this mixture, while Table 2 presents a comparison of calculated and experimental bubble and dew point densities for this mixture. The results in Tables 1 and 2 demonstrate that bubble points are predicted within about 2° F and dew points are predicted within about 3° F up to 500 psia and vapor and liquid densities are predicted within about 1% for pressures up to 450 psia. At 500 psia, the predicted vapor density is large and the predicted liquid density is small because the correlation predicts that the critical pressure is lower than the experimental critical pressure by about 5% (522.9 psia compared to the experimental critical pressure of 545.7 psia).

The fact that predicted bubble and dew point temperatures and densities for the normal butane - normal pentane mixture and enthalpies for the isobutane-isopentane mixture are predicted

TABLE 1. Comparison of Calculated and Experimental Bubble and Dew Point Temperatures for a 75.18 Mole Percent Normal Butane - 24.82 Mole Percent Normal Pentane Mixture.

Pressure, Psia	Bubble Point	Temp., °F	Dew Point	Temp., °F
	Exp.	Calc.	Exp.	Calc.
150	194.36	193.65	--	--
200	219.92	219.28	--	--
250	239.54	240.47	--	--
300	259.88	258.66	--	--
350	276.44	274.66	--	--
400	291.38	289.01	298.04	295.25
450	304.70	302.12	310.46	307.11
500	317.30	314.74	321.44	317.65

TABLE 2. Comparison of Calculated and Experimental Bubble and Dew Point Density for a 75.18 Mole Percent Normal Butane - 24.82 Mole Percent Normal Pentane Mixture.

Pressure, Psia	Bubble Point	Density	Dew Point	Density
	Exp.	Calc.	Exp.	Calc.
150	31.93	31.86	--	--
200	30.49	30.53	--	--
250	29.25	29.25	--	--
300	27.88	27.96	--	--
350	26.51	26.57	--	--
400	25.01	24.95	5.42	5.44
450	23.45	22.80	6.74	6.77
500	21.39	18.36	8.54	8.05

Density Units: lb(mass)/cu. ft.

reasonably accurately leads to the conclusion that conceptual design studies should be of acceptable accuracy using the correlation (excluding operating conditions in the near critical region).

5.8: Isobutane-Isopentane Mixture Transport Properties

The effort to evaluate data needs for isobutane-isopentane mixtures was curtailed before transport properties had been considered. However, we are aware that there are no available viscosity or thermal conductivity data for isobutane-isopentane mixtures. Thus, a data procurement program would seem advisable if these mixtures are used in major geothermal projects. Generalized three parameter corresponding states correlations of the viscosity and thermal conductivity of hydrocarbon mixtures can be used in the absence of data. The correlations in Appendix 3 probably are accurate with average absolute deviations less than 10% for isobutane-isopentane mixtures in geothermal cycle operating ranges.

6. Conclusions

This report presents thermophysical properties information which allows detailed geothermal binary cycle design calculations for a number of working fluids and conceptual design studies for many additional working fluids, including mixtures. The material in this report incorporates recent work with a number of previous studies. Data needs evaluations are presented for the thermophysical properties of isobutane, isopentane and isobutane-isopentane mixtures.

7. References

1. Starling, K. E., Fluid Thermodynamic Properties for Light Petroleum Systems, Gulf Publishing Co., Houston (1973).
2. Starling, K. E., Sliepcevich, C. M., Fish, L. W., Goin, K. M., Aboul-Fotouh, K. H., Kumar, K. H., Lee, T. J., Milani, J. S., Zemp, K. L., "Development of Working Fluid Thermodynamic Properties Information for Geothermal Cycles - Phase I," University of Oklahoma Report No. ORO-5249-2 to Department of Energy, December 31, 1977.
3. Starling, K. E. and Fish, L. W., "HSGC, A Mixture Thermodynamic Properties Computer Program," University of Oklahoma Report No. ORO-4944-2 to U.S. Energy Research and Development Administration, September 15, 1976.
4. Starling, K. E., L. L. Lee, K. C. Mo, C. H. Twu, et. al., "Self Consistent Correlation of Thermodynamic and Transport Properties," prepared for the Gas Research Institute and the American Gas Association, Final Report covering the period 1 Sept. 74 to 31 Dec. 77, CEMS, University of Oklahoma (1977).
5. Kestin, J., Khalifa, H. E., Kumar, B., "Thermodynamic and Transport Properties of Isobutane: A Survey of Available Data," Report COO/4051-35 (CATMEC/27), Brown University, (1979).
6. Private Communication from K. E. Starling to Max Klein, NBS, March 23, 1978.
7. Private Communication from Max Klein to K. E. Starling.
8. Sage, B. H. and Lacey, W. N., Thermodynamic Properties of the Lighter Paraffin Hydrocarbons and Nitrogen, American Petroleum Institute, New York (1950).
9. Beattie, J. A., Marple, S., Jr., Edwards, D. G., J. Chem. Phys., 18, (1), 127 (1950).
10. Agaev, N. A., A. D. Yusibova, "Viscosity of Isobutane at High Pressures," Gazovaya Promyshlennost, 14 (3), 41 (1969).
11. Gonzalez, M. H., A. L. Lee, "Viscosity of Isobutane," J. Chem. Engr. Data, 11 (3), 357 (1966).
12. Kazaryan, V. A., N. I. Ryabstev, "Thermal Conductivity of Isobutane," Gazove Delo, 10, 27, (1969).
13. Yusibova, A. D., N. A. Agaev, "Viscosity of Isopentane at High Pressures and Various Temperatures," Gazovaya Promyshlennost, 14, (6), 46 (1969).

14. Roberts, V. W. (Project Manager), "Experimental Enthalpies for a Mixture of 80 Mole Percent Isobutane in Isopentane," EPRI ER-1034, Project 928-4, prepared by C. F. Braun and Company for the Electric Power Research Institute (1979).
15. Private Communication from Gary Underhill, EPRI, to K. E. Starling.
16. Private Communication from K. E. Starling to Gary Underhill, EPRI, February 17, 1978.
17. Kay, W. B., Hoffman, R. L., Davies, O., "Vapor-Liquid Equilibrium Relationships of Binary Systems n-Butane - n-Pentane and n-Butane - n-Hexane," J. Chem. Engr. Data, 20 (3), 333 (1975).

APPENDIX 2

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App. 5 was a preprint - removed

App. 6 was a preprint -
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App. 7 was a preprint
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APPENDIX 8

The
University of Oklahoma

202 West Boyd, Room 23 Norman, Oklahoma 73019

College of Engineering
School of Chemical Engineering
and Materials Science

February 17, 1978

Dr. Gary Underhill
Electric Power Research Institute
Box 10412
Palo Alto, CA 94303

Dear Gary:

Enclosed are comparisons of predicted enthalpies with the C.F. Braun data.

We have made comparisons using the HSGC correlation, which utilizes a generalized modified Benedict-Webb-Rubin equation of state. This correlation is discussed in my book, "Fluid Thermodynamic Properties for Light Petroleum Systems", Gulf Publishing Company, 1973, in Chapters 17 and 18. The computer program used is the program given in ERDA Report ORO-4944-2, authored by L.W. Fish and myself in 1975.

The average absolute deviation (experimental minus calculated) of predicted enthalpies from experimental values is 5.07 Btu/lb, while the arithmetic average deviation is positive and equal to 3.45 Btu/lb. Predicted enthalpies are smaller than experimental values at 140 of the 199 points and on the average are smaller at all pressures except 80 psia.

There is good agreement between the trends of the predicted and experimental values, as can be noted on the temperature-enthalpy plot which is enclosed. This plot is a copy of the C.F. Braun plot with selected predicted points (shown as dots) and the predicted isobars (shown as dashed curves) added. It can be noted that the predicted isobars generally cross the experimental isobars within the two phase region. The major difference between the trends of the isobars is the fact that the predicted isobars are much straighter than the predicted isobars. Also, predicted dew and bubble point conditions differ from the values interpreted from the data. Bubble point enthalpies agree but the predicted bubble point temperatures are higher by about 5°F in the midrange of pressures. There are larger differences in dew points. It is interesting to note that the predicted dew and bubble points would be in better agreement with the data interpretation method in which enthalpies in the single and two phase regions are plotted as nearly straight lines, with the dew or bubble point estimate taken to be the intersection.

Dr. Gary Underhill
Page 2
February 13, 1978

It should be noted that changes in composition of the order observed during the experimental runs (e.g. 2 mole percent in isobutane and isopentane) would be sufficient to shift the predicted enthalpies to yield improved agreement. The compositions used in our calculations are the individual values given in the C.F. Braun tabulations (not a nominal or average composition). We would have performed some calculations to study the sensitivity to composition but could not justify the effort at this time.

With respect to cycle design implications, it should be noted that the condenser duty in the condensing region would be predicted within 1-2 Btu/lb out of about 138 Btu/lb (approximate enthalpy of condensation). Depending on the turbine inlet pressure, the brine heat exchanger duty would be predicted within 2 to 5 Btu/lb out of about 180 Btu/lb between an inlet enthalpy of 30 Btu/lb (saturated liquid at 125°F) and an outlet enthalpy of 210 Btu/lb (could be supercritical or subcritical cycle). The accuracy of these predictions is adequate for most design purposes. The main problems arise with respect to (1) the location of the saturated vapor (dew point) locus and (2) the enthalpy drop in the turbine. I don't think the data obtained to date are sufficient to answer either of these questions. What is needed are additional data, (1) vapor-liquid equilibrium data to define the dew point locus, but also the bubble point locus and compositions of vapor and liquid in equilibrium, (2) pressure-volume-temperature data and (3) expansion data in the region of turbine expansion. The preferable expansion data are isothermal expansion data, but Joule-Thomson data would be useful if isothermal expansion data cannot be obtained.

I hope our calculations and comments will be helpful to you in your effort to meet the needs for data on this project. We will be glad to provide additional assistance. I will appreciate your permission to provide copies of this correspondence and future related correspondence on this matter to Clifton McFarland (ERDA), Joseph Kestin (Brown U.) Ken Mirk/Leonard Silvester (LBL) and Jud Whitbeck/Larry Fish (INEL).

Yours truly,

Kenneth E. Starling,
Professor

KES/yv

TABLE II

SATURATED LIQUID DENSITIES FOR
THE NOMINAL 80-20 ISOBUTANE -
ISOPENTANE MIXTURE

TEMPERATURE
DEGREES F

DENSITY
GMS/ML (1)

60

0.568

~~75~~

0.561 ← 1.566

80

0.562

NOTE 1 At each temperature, duplicate measurements gave identical results.

Comparison of Modified BWR Correlation for Isobutane
(1977 Parameters) with Experimental Enthalpy Data

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FIGURE 1

ENTHALPIES FOR ISOBUTANE
ALONG THE 250 PSIA ISOBAR

EPRI
PALO ALTO

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Comparison of HSGC Correlation (— and ---) with Experimental Enthalpy Data

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FIGURE 2

ENTHALPY OF MIXTURE OF NOMINAL
80 MOLE PERCENT ISOBUTANE IN ISOPENTANE

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EPRI
PALO ALTO